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High Rate Plasticity under Pressure using a Windowed Pressure-Shear Impact Experiment

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Abstract. An experimental technique has been developed to study the strength of materials under conditions of moderate pressures and high shear strain rates. The technique is similar to the traditional pressure-shear plate-impact experiments except that window interferometry is used to measure both the normal and transverse particle velocities at a sample-window interface. Experimental and simulation results on vanadium samples backed with a sapphire window show the utility of the technique to measure the flow strength under dynamic loading conditions. The results show that the strength of the vanadium is 600 MPa at a pressure of 4.5 GPa and a plastic strain of 1.7%.

Keywords: transverse waves, vanadium, strength.
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INTRODUCTION

Many experiments and analysis techniques have been developed to determine the compressive flow stress of materials under impact conditions [1-3]. Most of these experiments, however, analyze the longitudinal wave, and while extremely useful, are usually limited by requiring an accurate equation of state for the material. In addition, while the longitudinal wave is rich with information about the elastic and plastic state of the material, the plasticity can be masked by the usually much larger elastic response. Pressure-shear techniques have been developed to measure the shearing response of materials by measuring the transverse waves, which are much more sensitive to the strength of the material [4, 5]. The technique described here is similar to the pressure-shear experiment, expect that window interferometry is used, which allows for the potential of higher pressures to be achieved. Espinosa [6] developed a similar technique to explore the failure of ceramic materials, and we are extending that technique to study the strength of metals. The key component is the measurement of the transverse wave, which is sensitive to the strength and whose interpretation is not as reliant on knowledge of the equation of state.

EXPERIMENTAL PROCEDURE

A schematic of the experimental set-up is shown in Fig 1. A 31.75 mm diameter, 3 mm thick Ta-10W flyer is used to impact a 31.75 mm diameter, 1.5 mm thick polycrystalline vanadium target that is backed by a 31.75 mm diameter, 10mm thick single crystal c-cut sapphire window. Both the longitudinal and transverse waves are measured through the window at the V/sapphire interface, utilizing two interferometric techniques, the normal displacement interferometer (NDI) and the transverse displacement interferometer (TDI) [7].

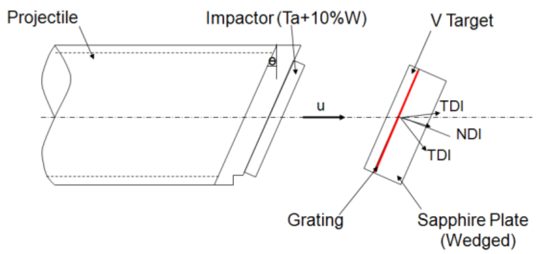

Figure 1. Schematic of the experiment.

In order to measure the transverse waves, a diffraction grating of 1200 lines/mm is applied into the sapphire using laser lithographic techniques and a dry etching process. The lines, which are nominally 85 nm in depth, are filled with a 120 nm thick sputter deposited vanadium coating. The vanadium sample is then attached to vanadium coating side of the sapphire window by placing glue around the circumference of the sample. Since the longitudinal wave runs faster than the shear wave, any small local perturbation will have been compressed by the time the shear wave arrives.

The experiments are performed on the 2.5" diameter keyed gas gun in the Plate Impact Facility at Brown University. The impact velocities for the experiments were approximately 200 m/s and the angle between the direction of the flight and the impact face is 18 degrees. The keyway prevents rotation during the experiment. It should be noted that while the impact face is at an angle to the flight, the faces of the flyer and the samples are flat and parallel to each other. The flatness of the samples are within 4 waves over the area, and are parallel to better than 0.1 milliradians.

For this experiment the shear window ends when the longitudinal wave reaches the rear surface of the sapphire. At this time, there is a small transverse component, caused by any small amount of tilt between the flyer and sample, which runs with the longitudinal wave. It is this transverse component that interferes with the TDI signal when it reaches the rear surface.

Strength Model

In order to back out the strength of the material, a 2-D hydrodynamics code with a rate dependant Steinberg-Lund strength model [8] is used. For review, the Steinberg-Lund model takes the following form:

$$Y = [Y_T(\dot{\varepsilon}, T) + Y_A(\varepsilon_p)]\frac{G(P,T)}{G_o} \qquad (1)$$

where Y_A is the rate independent athermal stress and is a function of the plastic strain through the conventional power law hardening parameters β and n . Y_T contains the strain rate dependent part of the flow stress, G_o is the shear modulus, and G(P,T) describes how the shear modulus changes as a function of temperature and pressure. The strain rate dependant part, Y_T follows the Hoge-Mukherjee model as:

$$\dot{\varepsilon} = \left\{ \frac{1}{C_1} \exp\left[\frac{2U_k}{kT}\left(1 - \frac{Y_T}{Y_p}\right)^2 \right] + \frac{C_2}{Y_T} \right\}^{-1} \qquad (2)$$

where $2U_k$ is the energy needed to form a pair of kinks, Y_p is the Peierls stress, C_1 is a coefficient that contains the lattice information, and C_2 contains the phonon drag coefficient, which is related to the energy required for the dislocations to move past the phonon vibrations of the lattice [9]. Therefore, the strain rate dependant part of this model can be viewed as containing two parts, the left hand side of the summation referring to the regime that is limited by the energy to overcome the dislocation barriers, known as the thermally activated regime, and the right hand side of the sum representing the phonon drag contribution.

RESULTS AND DISCUSSION

Table 1 contains a summary of the velocities and thicknesses for the two vanadium shots. Fig. 2

TABLE 1. Experimental parameters for the pressure-shear windowed vanadium experiments

Shot #	Flyer velocity (m/s)	Flyer thickness (mm)	Sample thickness (mm)	P, GPa
V1	204	3.0	1.54	4.5
V2	197	2.9	1.51	4.5

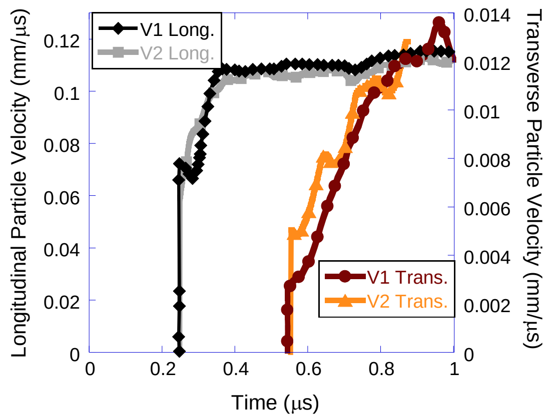

Figure 2. Experimental longitudinal and transverse waves measured at the V/sapphire interface.

shows that the experimental wave profiles, measured at the sample window interface, are nominally the same, with the longitudinal wave showing an elastic precursor at approximately 0.07 mm/µs, and then reaches a plateau at 0.11 mm/µs. The transverse wave shows an initial sharp rise when it arrives, followed by a gentler increase in the particle velocity as a function of time up to the end of the shear window.

There is a slight discrepancy between the two experiments in that for the first vanadium experiment, V1, there is a sharp drop near 0.07 mm/µs in the longitudinal signal before it rises again, where in the second experiment, V2, there is no drop. In addition, for the shear waves, the initial rise for V1 is nearly half of that for V2, although at later times the two curves converge.

The nature of the differences in the two experiments are unknown, but it appears that for the first experiment there is a small release event that is occurring, which could perpetuate to the transverse velocity signal causing a lower initial rise. The fact that they achieve a similar state at later times is indicative that the strength of the two materials is nominally the same.

Using the LLNL hydrodynamics code ALE3D, with a 2-D mesh size of 10 microns, a Steinberg-Lund (S-L), model was used to try and reproduce the experimental data. A comparison between the experiment V2 and the simulations are shown in Fig 3, and the model parameters used to "fit" the data are shown in Table 2. The nominal model parameters used for vanadium are taken from Steinberg's handbook [10]. In order to match the experimental data, Y_p has been lowered, and Y_A has been increased. Lowering the Peierls stress effectively lowers the strain rate dependence on the model, and increasing Y_A increases the effect of strain hardening. These numbers are consistent with a Peierls stress of 568 MPa estimated from Dorn and Rajnak [11].

With these parameters the model compares very closely with the experimental data. The rate dependence in the model does a good job of capturing both the elastic precursor in the longitudinal wave, and the initial rise in the transverse wave. During the initial rise from the longitudinal wave, which is deforming the material at very high rates (> 10^5 1/s), the flow stress in the material is very high. After the fast rise however, both the flow stress and strain rate drop. When the transverse wave arrives at a later time, there is another increase in the strain rate, and therefore an initial elastic response, before the material again hits the yield surface.

With this experiment, the longitudinal wave can be viewed as deforming the material at high rates (> 10^5 s^{-1}) at pressure, and the transverse wave can be viewed as a probe of that deformed state. While there is not necessarily a unique set of model parameters that can reproduce the data, since the transverse wave is sensitive to the flow stress, each set of model parameters must predict nominally the same flow stress when the shear wave arrives in order to match the data. Using this

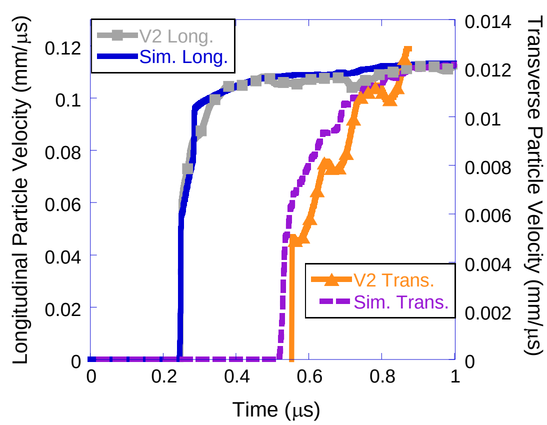

Figure 3. Comparison between the experimental data and the Steinberg-Lund strength model.

TABLE 2. Steinberg- Lund model parameters for vanadium

Parameters	This study	Steinberg Handbook [10]
Y_A (Mbar)	2.75E-3	1.5E-3
β	10	10
n	0.1	0.1
y^*_{max} (Mbar)	8.3E-3	8.3E-3
C_1 (μs^{-1})	0.71	0.71
U_k (ev)	0.31	0.31
Y_p (Mbar)	5E-3	8E-3
C_2 (Mbar- μs)	0.12	0.12

methodology, these samples have a flow stress of 600 MPa at 4.5 GPa pressure after 1.7% strain. This value is consistent with other studies on vanadium if the strain rate dependence is extrapolated to strain rates of 10^5 [12].

CONCLUSIONS

A technique has been developed for measuring the strength of materials under dynamic loading conditions. An interferometric technique was used to measure the transverse wave through a window backer material. The benefit of this technique is the high sensitivity of the shear wave to the strength of the material, and while a model is needed to extract the yield strength, the strength model is much less dependent on the EOS than previous models.

Utilizing this technique, a polycrystalline vanadium sample has been measured and has a flow stress of 600 MPa, at a pressure of 4.5 GPa, after 1.7% strain.

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